6. Properties of Ionic and Covalent Compounds

Objectives

Determine if an unknown substance is an ionic, polar covalent, or non-polar covalent compound based on its physical properties. Through this investigation, students:

- Review physical properties, including conductivity, solubility, hardness, and melting point
- Determine differences in physical properties for ionic and molecular covalent compounds
- Explain the differences between intramolecular and intermolecular forces

Procedural Overview

Students conduct the following procedures:

- Test the conductivity, solubility, hardness, and melting point of ionic, polar covalent, and non-polar covalent compounds
- Identify an unknown substance as an ionic, polar covalent, or non-polar covalent compound

Time Requirement

Preparation time	10 minutes
Pre-lab discussion and activity	30 minutes
Lab activity	45 minutes

Materials and Equipment

For each student or group:

- Data collection system
- Conductivity sensor
- Hot plate
- Graduated cylinder, 10-mL
- Test tube (5), 15-mm x 100-mm
- Test tube rack
- Stopper, (3) to fit the test tubes
- Spatula
- Tongs
- Aluminum foil square (6), 5-cm x 5-cm
- Masking tape
- Wash bottle and waste container
- Distilled (deionized) water, 30 mL
- Table salt (NaCl), 1 g
- Table sugar ($C_{12}H_{22}O_{11}$), 1 g
- Paraffin wax, 1 g
- Unknown A, 1 g[1]
- Unknown B, 1 g[1]
- Unknown C, 1 g[1]

[1] Use glucose (also called dextrose, $C_6H_{12}O_6$) for unknown A; use crayon pieces for unknown B; and use potassium chloride (KCl) for unknown C.

Concepts Students Should Already Know

Students should be familiar with the following concepts:

- Physical properties
- Types of bonds
- Polar versus non-polar molecules

Related Labs in This Guide

Labs conceptually related to this one include:

- Density
- Electrolyte versus Non-Electrolyte Solutions

Using Your Data Collection System

Students use the following technical procedures in this activity. The instructions for them (identified by the number following the symbol: "�") are on the storage device that accompanies this manual. Choose the file that corresponds to your PASCO data collection system. Please make copies of these instructions available for your students.

- Starting a new experiment on the data collection system �(1.2)
- Connecting a sensor �(2.1)
- Monitor live data �(6.1)

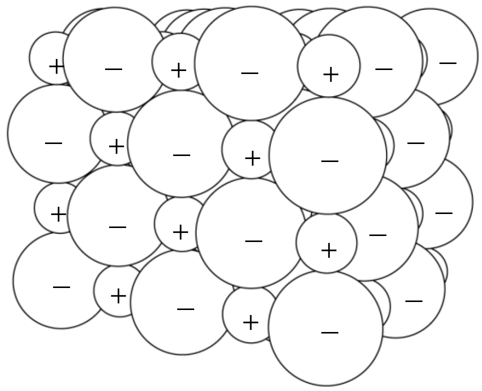
Background

In nature, a wide variety of forces exist. In chemistry, different electrical forces of attraction hold substances together. These electrostatic forces are the result of atoms interacting with electrons (subatomic particles with negative charge). Within the nucleus exists protons (subatomic particles with positive charge); it is the attraction between the positively charged nucleus and the outer negatively charged electrons that result in electrostatic forces of attraction.

Atoms are chemically bonded to each other as a result of intramolecular forces. These bonds exist within molecules because of a sharing of electrons between two bonding atoms. When each atom contributes an electron to the pair being shared between two atoms, it is called a covalent bond. If one atom shares a pair of electrons originally belonging to only itself with another atom, the result is a coordinate covalent bond. Metallic bonding occurs when electrons are equally distributed between a number of metal atoms, such that they are surrounded by a “sea of electrons.”

In some pairings of atoms (those between a metal and a non-metal), the electron is not shared. Instead, it is completely transferred from the metal to the non-metal. In such an instance, the metal completely loses one or more electrons and becomes positively charged, forming an ion (cation), while the non-metal completely gains the electrons and becomes negatively charged forming an ion (anion). Here, opposite charges attract the ions together much like a collection of magnets. The resulting electrostatic interaction forms an ionic bond.

The mass of alternating positive and negatively charged ions forms a crystal lattice. Because the units are not discrete, compounds formed between ions are not able to be called molecules. Instead, they are referred to as ionic compounds.

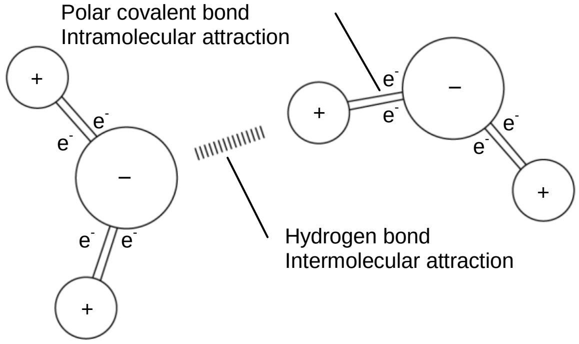


Sodium chloride in a solid crystal lattice arrangement.

Differentiating between covalent and ionic bonds depends upon the relative degree that the electrons are shared between atoms. This differentiation is based on the individual atoms' tendencies to gain or lose electrons, measured as electronegativity. Electronegativity is ordered on the Pauling scale (named after the American chemist, Linus Pauling) and has a range of 0 to 4. The larger the electronegativity value, the greater the atom's tendency to gain an electron.

Electronegativity differences between two atoms determine the bond classification: those with differences greater than 1.7 are considered ionic and those with differences less than 1.7 are considered covalent. With covalent bonding, even though electrons are shared an atom in the pair might have a greater affinity for the electrons. In these instances (electronegativity differences between 0.5 and 1.7), the electron is not equally shared and results in a polar bond, where the negative charge of the electron resides heavily with the atom with the greater electronegativity. For those pairings of atoms where there is not a great difference in tendency to gain or lose electrons (electronegativity values less than 0.5), the electron is equally distributed between the two atoms and results in a non-polar bond.

Neighboring molecules may also feel the attractions between the nuclei within its own molecule and the electrons of the molecule next to it. Intermolecular forces hold molecules together to form liquids and solids and are much weaker than the forces holding atoms together to form individual molecules. These intermolecular forces can be overcome with the input of energy. This causes solids to melt and liquids to boil, simply by overcoming the intermolecular forces holding the molecules to one another.



Water molecules

The properties of a substance are a direct result of the different intramolecular and intermolecular forces that exist because of the substance's composition and structure. Because atoms and molecules cannot be seen directly (even with the most powerful microscopes), chemists must rely upon macroscopic properties, such as conductivity, hardness, melting point, and solubility to determine the types of attractions present for a particular substance.

Pre-Lab Discussion and Activity

Demonstrations

Engage the students in a discussion about why different substances behave differently by demonstrating the following situations. Hold up a piece of chalk and a piece of plastic in front of the class and drop both of them. Next, place a packaging peanut in a beaker of water and another packaging peanut in a beaker of acetone (or nail polish remover). Discuss the results, emphasizing that different materials behave in different ways.

1. What happened to the chalk and the plastic when dropped? Why?

The chalk broke into pieces but the plastic did not change. Chalk and plastic consist of different substances that are held together with different types of chemical bonds.

2. What are packaging peanuts made up of?

Packaging peanuts are made up of plastic (polystyrene) and air.

3. Do packaging peanuts behave the same way in water and acetone?

Packaging peanuts remain unchanged when placed in water. When placed in acetone, however, the packaging peanuts dissolve and the air inside of them is released.

4. Why do packaging peanuts behave differently in water and in acetone?

Water molecules and acetone molecules are different and contain different types of bonds. Water is a polar substance and polystyrene is a non-polar substance so polystyrene does not dissolve. Acetone, on the other hand, has non-polar bonding and, therefore, dissolves the polystyrene.

Teacher's Tip: The rule "like dissolves like" can be included as a discussion topic here.

Ways That Atoms Combine to Form Macroscopic Matter

Review that the properties of matter are explained by the atoms that make them up and the way in which these atoms bond. Show a model of an ionic lattice structure, a covalent lattice structure, and a model (or drawing) of how molecular substances establish intermolecular attractions to form macroscopic matter.

5. What makes up all the different types of matter?

There are 117 known atomic elements which all have different properties and behaviors. In addition to their individual atomic properties, these atoms can also bond with other atoms to form the vast array of different types of compounds making up matter.

6. If atoms are so small they cannot be seen, even with a microscope, how is it possible that we can see matter?

Matter is made up of lots of atoms. We may not be able to see one atom, but when we have enough of them we can see them.

Teacher's Tip: Demonstrate this by putting one small grain of sand into a large jar and holding it at a distance. Compare this to when the jar is filled with sand.

7. How do atoms combine? What are these structures called?

Atoms combine in different ways. Some atoms bond to other atoms in lattice structures to form ionic compounds, while other atoms combine together into molecules and the molecules are held to each other by intermolecular forces.

8. Based on your understanding of how atoms combine, explain why the chalk broke when it was dropped and the plastic did not?

Chalk breaks when it falls because the ions in the lattice structure are shifted so that like charges are next to each other and they repel, causing the chalk to break. The plastic on the other hand did not break because it does not contain charged particles. Plastic is made up of molecules (macromolecules) that are intertwined with each other. When plastic hits the ground, the group of molecules shifts, but there is no sudden repulsion and, therefore, no breakage.

9. Why is water a liquid at room temperature, but oxygen is a gas?

Both water and oxygen are covalent molecular substances. The difference in their state of matter at room temperature is due to the strength of the intermolecular forces holding the molecules together. Water molecules are polar and oxygen molecules are non-polar. The polar water molecules are held together with stronger intermolecular attractions than the non-polar oxygen molecules.

Properties of Matter Explained

Substances that contain similar bonds have similar properties. So if you know the type of bonding in a substance, the material properties can be predicted. The reverse is also true. If you know the properties of a certain substance, then the bonding involved can be inferred.

10. How can you explain why certain substances have characteristic properties?

The properties of the substance are based on the type of atoms in the substance and the way they are bonded.

11. How can you predict the types of bonding in a given substance?

If you know the general properties of certain types of bonding, you can use the properties to predict the type of bonds in the substance.

Lab Preparation

These are the materials and equipment to set up prior to the lab.

Place the unknown substances in containers labeled "unknown A", "unknown B", and "unknown C".

Recommended unknowns are:

Unknown A: a polar covalent compound such as glucose (commonly called dextrose, $C_6H_{12}O_6$) or aspartame ($C_{14}H_{18}N_2O_5$), an artificial sweetener

Unknown B: a non-polar covalent compound such as crayons

Unknown C: an ionic compound such as potassium chloride (KCl)

Safety

Add these important safety precautions to your normal laboratory procedures:

- ♦ The hot plate gets extremely hot. Avoid contact with the hot plate until it has completely cooled.
- ♦ Keep all materials, especially electrical cords and paper, away from the hot plate while it is hot.

Sequencing Challenge

The steps below are part of the Procedure for this lab activity. They are not in the right order. Determine the proper order and write numbers in the circles that put the steps in the correct sequence.

4	3	1	2
Identify the bonding characteristics of the unknown compounds.	After testing the known compounds, test the physical properties of each of the unknown substances.	Obtain the equipment and label all materials that will be used in the experiment.	Test 4 different physical properties for each of the known compounds.

Procedure with Inquiry

After you complete a step (or answer a question), place a check mark in the box (☐) next to that step.

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Set Up

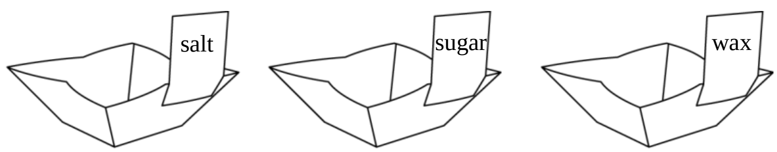
1. ☐ Plug in the hot plate and set it to its highest setting.

2. ☐ Place four test tubes in a test tube rack. Label the test tubes “salt”, “sugar”, “wax”, and “distilled water”.

3. ☐ Create and label three aluminum foil dishes.

a. Fold three pieces of aluminum foil (5-cm × 5-cm squares) into small dishes.

b. Place a piece of tape on each dish and label the dishes “salt”, “sugar”, and “wax”. These dishes will eventually be placed on the hot plate, so make sure that the label is positioned so that it will not directly touch the heating surface.



4. ☐ Why is it important to label the test tubes and aluminum dishes?

Many substances have similar appearances. By labeling their containers, you avoid confusion.

5. ☐ Use a spatula to place a pea-sized sample of each substance in the appropriately labeled aluminum dish and another pea-sized sample of each substance in the appropriately labeled test tube.

Collect Data

6. ☐ Test the hardness of each compound by rubbing a small sample between your fingers. Record the hardness as either soft and waxy, or brittle and granular. Record your observations in Table 1 below. Wash your hands after testing.

Table 1: Observed physical properties of salt, sugar, and wax

Physical Property	Ionic Compound: salt (sodium chloride)	Covalent Compound Polar Molecular: sugar (sucrose)	Covalent Compound Non-polar Molecular: wax
Hardness (soft and waxy or brittle and granular)	brittle and granular	brittle and granular	soft and waxy
Melting point (high or low)	high	low	low
Soluble in water (yes or no)	yes	yes	no
Conductivity in water (µS/cm)	56,223	59	14
Conductor or non-conductor	conductor	non-conductor	non-conductor

7. ☐ Place the aluminum dishes containing the samples onto the hot plate and heat them for a maximum of three minutes. If a substance melts, use tongs to carefully remove the aluminum dish from the hot plate, allow it to cool, and record the melting point as low (in Table 1 above).

8. ☐ After three minutes of heating, turn the hot plate off. If a substance did not melt, record its melting point as high in Table 1 above.

9. ☐ Explain the types of bonds that are being overcome during the melting of ionic and covalent molecular compounds.

For ionic compounds, the ionic bonds must be overcome for the substance to melt.

For covalent molecular compounds, the intermolecular attractions must be overcome for the substance to melt.

10. ☐ Fill each of the test tubes containing the separate samples with approximately 5 mL of distilled water.

11. ☐ Stopper each test tube and gently shake the test tubes for two minutes or until dissolved.

12. ☐ Observe each test tube and record whether the substance dissolved or not. Record your observations in Table 1 above.

13. ☐ Start a new experiment on the data collection system. �(1.2)

14. ☐ Connect the conductivity sensor to the data collection system. �(2.1)

15. ☐ Configure your data collection system to monitor conductivity in a digits display. �(6.1)

16. ☐ Set the range of the conductivity to its lowest setting (0 to 1000 µS/cm) by pressing the green button marked with .

17. ☐ Test the conductivity of the distilled water by placing the conductivity sensor in the test tube filled with distilled water. Record the results below.

Conductivity of distilled water (µS/cm): ___14 µS/cm___

18. ☐ Test the conductivity of the three remaining samples by following the steps below:

a. If the substance did not completely dissolve, decant the solution into another test tube.

b. Place the conductivity sensor in the test tube containing the decanted liquid.

c. Start with the conductivity sensor at its lowest setting: (0 to 1000 µS/cm). If the conductivity sensor is saturated (reads 1000 µS/cm), then change to the middle setting (0 to 10,000 µS/cm). If the conductivity sensor is saturated at the middle setting (reads 10,000 µS/cm), then change to the highest setting (0 to 100,000 µS/cm).

d. Record the conductivity (µS/cm) in Table 1 above.

e. Clean the conductivity sensor using distilled water and then repeat for the next sample.

19. ☐ If the conductivity is similar to distilled water, record the sample as a non-conductor in Table 1 above. If the conductivity of the sample is much greater (100 times or more) than the distilled water, record the sample as a conductor in Table 1 above.

20. ☐ What does conductivity indicate about the molecular structure of a compound?

Conductivity occurs when there is a flow of charged particles. If a substance conducts electricity, then it must be composed of ions that are free to move.

21. ☐ Dispose of the solutions and solids and clean the glassware so that it can be used to test the unknowns.

22. ☐ Obtain the unknown samples and repeat the experiment to find the properties of each of the unknown substances. Record the results in Table 2 below.

Table 2: Observed physical properties of unknowns

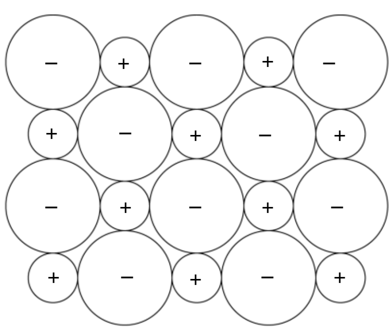
Physical Property	Unknown A	Unknown B	Unknown C
Hardness (soft and waxy or brittle and granular)	hard and brittle	soft and waxy	hard and brittle
Melting point (high or low)	low	low	high
Soluble in water (yes or no)	yes	no	yes
Conductivity in water (µS/cm)	25	32	43,011
Conductor or non-conductor	non-conductor	non-conductor	conductor

23. ☐ Clean the lab station according to the teacher's instructions.

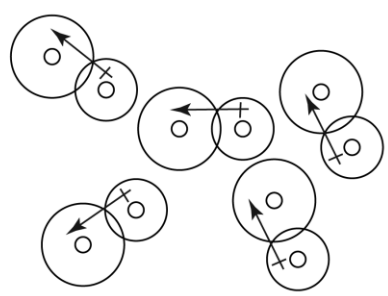
Data Analysis

1. ☐ Draw pictures that illustrate the molecular structure of each of the following:

Ionic compounds:



Molecular Polar Covalent Compounds:



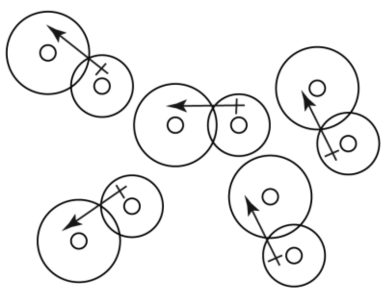
Molecular Non-polar Covalent Compounds:

2. ☐ Identify the molecular bonding (compound type) of unknown A, unknown B, and unknown C, and briefly explain the evidence supporting your decision.

Unknown	Type of Bonding	Evidence
Unknown A	polar molecular covalent compound	low melting point, soluble in water, low conductivity
Unknown B	non-polar molecular covalent compound	low melting point, insoluble in water, low conductivity
Unknown C	ionic compound	high melting point, soluble in water, high conductivity

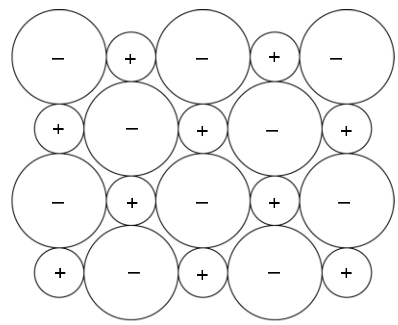
3. ☐ Draw pictures that illustrate the molecular structure of unknown A, of unknown B, and of unknown C.

Unknown A



Unknown B

Unknown C



Analysis Questions

1. How can you determine if an unknown substance is an ionic compound or a molecular covalent compound (either polar or non-polar)?

Observe the macroscopic properties of the substance. Substances that dissolve in water, conduct electricity, and have a high melting point are ionic compounds. Substances that do not dissolve in water, do not conduct electricity, and have low melting points are molecular covalent compounds.

2. What properties are the same for ionic and molecular covalent compounds (either polar or non-polar)?

Both may be hard and granular, and both may be soluble in water.

3. What is the difference between an ionic bond and an ionic compound?

Ionic bonds exist between two atoms. Ionic compounds are an entire network (lattice structure) of ionic bonding between many atoms.

4. What properties can be used to determine if a molecular covalent is polar or non-polar?

Polar covalent molecules will have high melting points and will be soluble in water while non-polar covalent molecules will have low melting points and will not be soluble in water.

Synthesis Questions

Use available resources to help you answer the following questions.

1. What are the two main chemical components of air? Predict the type of bonding for each. Explain your reasoning.

Air is approximately 78% nitrogen and 21% oxygen. The remaining 1% is other gases, including argon, carbon dioxide, and water vapor.

Both nitrogen and oxygen gases are non-polar covalent compounds. They both must have very low melting points because they exist as gases at room temperature.

2. Odor is another physical property that can be tested. Which type of compounds (ionic or molecular covalent) would you expect to have a stronger odor? Why?

Covalent compounds have lower melting points and require less energy to overcome the intermolecular forces holding the molecules together in solid form. This also applies to the intermolecular forces that must be overcome for the molecules to vaporize into individual gas molecules of the substance. The substance must be in vapor form so that the molecules can enter the nose and be smelled.

3. Oil does not dissolve in water. Based on this observation, would you classify oil as a non-polar covalent, polar covalent, or ionic compound? Explain.

Oil is a non-polar covalent compound. If oil were ionic or polar covalent, it would dissolve in water.

Multiple Choice Questions

Select the best answer or completion to each of the questions or incomplete statements below.

1. Which of the following is a property of an ionic compound?

- **A.** Conducts electricity in the solid state
- **B. Conducts electricity when dissolved in water**
- **C.** Has a low melting point
- **D.** Is soft and waxy

2. How are molecules in covalent compounds held together?

- **A. Intermolecular forces**
- **B.** Intramolecular forces
- **C.** Ionic bonds
- **D.** Covalent bonds

3. What substance most likely exists as a gas at room temperature?

- **A.** Ionic compound
- **B.** Polar covalent compound
- **C. Non-polar covalent compound**
- **D.** Metal

4. What substance most likely does not dissolve in water?

- **A.** Ionic compound
- **B.** Polar covalent compound
- **C. Non-polar covalent compound**
- **D.** Gaseous compound

5. What substance most likely dissolves in water but in solution does not conduct electricity?

- **A.** Ionic compound
- **B. Polar covalent compound**
- **C.** Non-polar covalent compound
- **D.** Metal

Key Term Challenge

Fill in the blanks from the list of words in the Key Term Challenge Word Bank.

1. **Intramolecular** forces cause atoms to be attracted to one another within molecules. These forces result when the **positive** charged nuclei of two atoms are attracted to the same set of **negative** charged electrons. If the electrons are shared between the atoms, then a **covalent** bond is formed. If the electrons are taken completely by one atom, the atom becomes an ion and forms **ionic** bonds.

2. Atoms do not have the same tendencies to gain and lose electrons. **Electronegativity** is the measure of how much an atom tends toward gaining an electron. When one atom in a **covalent** bond has a greater affinity for the electron, a **polar covalent** bond is formed because the electron is **unequally** shared between the bonding atoms. If the electrons are **equally** shared, then the negative charge is distributed between the atoms equally forming a **non-polar covalent** bond.

3. When forces of attraction exist between neighboring molecules, they are called **intermolecular** forces. These forces are **weaker** than the forces holding atoms together and cause the molecules to form solids and liquids. The types of forces holding atoms and molecules together give substances their different **physical** properties, such as **melting point**, electrical **conductivity**, and **solubility** in water.

Extended Inquiry Suggestions

Investigate whether the amount of the substances tested affects the physical properties measured in this investigation (intensive versus extensive properties).

Investigate a variety of liquids to determine which is the most polar.

Ask students to draw and/or build molecules of these compounds to help them visualize the unequal distribution of charge in polar bonds and polar molecules.

Explore the effects of temperature on the solubility of an ionic substance.